

Joint Communication-Motion Planning in Wireless-Connected Robotic Networks: Overview and Design Guidelines

Bo Zhang, Yunlong Wu, Xiaodong Yi, Xuejun Yang

Abstract—Recent years have witnessed the prosperity of robots and in order to support consensus and cooperation for multi-robot system, wireless communications and networking among robots and the infrastructure have become indispensable. In this technical note, we first provide an overview of the research contributions on communication-aware motion planning (CAMP) in designing wireless-connected robotic networks (WCRNs), where the degree-of-freedom (DoF) provided by motion and communication capabilities embraced by the robots have not been fully exploited. Therefore, we propose the framework of joint communication-motion planning (JCMP) as well as the architecture for incorporating JCMP in WCRNs. The proposed architecture is motivated by the observe-orient-decision-action (OODA) model commonly adopted in robotic motion control and cognitive radio. Then, we provide an overview of the orient module that quantify the connectivity assessment. Afterwards, we highlight the JCMP module and compare it with the conventional communication-planning, where the necessity of the JCMP is validated via both theoretical analysis and simulation results of an illustrative example. Finally, a series of open problems are discussed, which picture the gap between the state-of-the-art and a practical WCRN.

Keywords—Joint communication-motion planning, robotics networks, learning (artificial intelligence), fading channels, dynamic programming

I. INTRODUCTION OF JCMP AND RELATED WORKS

Recent years have witnessed the evolution of robotics and great industrial/academic efforts. As the robots interact with the physical and social environments, considerable research contributions have been devoted to robotic sensing, cognition, motion/path planning and control[1]. A multi-robot system aims at achieving challenging tasks or significantly improving mission performance compared with a single robot, which demands consensus and cooperation among robots [2]. Therefore, maintaining the connectivity quality for information exchange among robots becomes vital. As mobile robots are less likely to be connected via wires, the wireless communications and networking among robots and the infrastructure would play an crucial role and the wireless-connected robotic networks (WCRNs) are very likely to be incorporated into the next-generation communication networks.

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A. Overview of CAMP

There is growing interest in incorporating autonomous robots into wireless communication networks[3], [4], [5], [6], [7], [8], [9], [10], [11], and most contributions focuses on designing communication-aware motion planning (CAMP) for different applications.

In [3], Lindhe and Johansson suggested exploiting multipath fading by motion plan in order to achieve a higher channel capacity, while Gil et al. utilized the directional signal strength information to design a simple positional controller by adapting to wireless signals in real-world environments[11]. In [4], Tekdas et al. adopted mobile robots for collecting data from wireless sensor networks (WSNs) in order to extend the lifetime of the sensor system by reducing the communication energy consumption of the sensing nodes. Ghaffarkhah and Mostofi proposed to exploit the mobility of mobile robots for improving the performance of wireless channel assessment and target tracking in[5], as well as minimizing the probability of target detection error for surveillance, while guaranteeing connectivity constraints in [6]. Kudelski et al proposed that a group of robots may exploit mobility to effectively and rapidly learn the link quality model in an unknown environment[10]. Daniel et al considered the sensing task by multiple coordinated unmanned ariel vehicles (UAVs) , where both the self-organizing mesh networking and channel-aware mobility control contributes to a more timely and accurate information data collection and fusion. Kim and Seo proposed a spatially secure group communication problem, where the mobility of the UAVs were planned to occupy a smaller space in order to improve the group security, while preventing from becoming a over-dense group to avoid communication congestion[8]. Fink et al. proposed to combine adaptive routing and motion control for maximizing the probability of having a connected network[12], [9]. Considering a mobile robot visiting several point-of-interests while communicating with a base station, Yan and Ali et al aimed at minimizing the total energy consumption and adopted mixed integer linear program [13] and the optimal control methods[14].

According to the above contributions, *CAMP may be summarized as to utilize the knowledge of connectivity quality for planning the robotic motion in order to improve specified task-oriented performance, while satisfying certain communication constraints*[5]. Therefore, CAMP focuses on exploiting the mobility resources in order to optimize the motion plan, while the communication schemes are fixed or having a limited

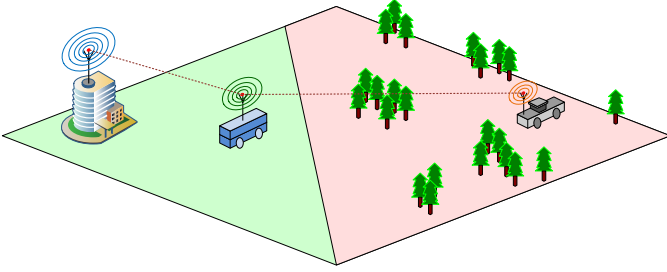


Figure 1. The scenario of a sensing robot survey a sensitive area, and transmit the monitored information to a base station.

adaptive capability so that the communication quality has to be guaranteed by motion plan[13]. Although some works have considered adaptive transmission schemes such as adaptive transmission rate[13] and routing[12], *they are far away from fully exploiting the degree-of-freedom (DoF) in space, time, frequency and energy dimensions in optimizing the communication quality for supporting the mission objectives*. Let us take two simple examples of robot surveillance in order to illustrate the above assertion. The scenario is illustrated in Fig. 1, in which a sensing robot explores the area and tracks any targets of interest, then transmits the sensing data to the base station.

In the first example, the wireless channel quality is heavily degraded due to the shadowing of an obstacle, e.g. several trees. In this scenario, the sensing robot may exploit its mobile capability to move away from the shadowing area and to find a better spot for communications[3]. Another solution is to deploy a router robot to build up a new relay-aided link spanning from the sensing robot to the base station, which detours the deep-shadowed communication channels[15]. In this example, the CAMP may greatly improve the communication quality by exploiting the DoF in mobility.

In the second example, the wireless channels between the sensing robot and the base station is heavily interfered in the time-frequency domain. In this case, exploiting the mobility of the robots or deploying router robots may not achieve a noticeable improvement in the communication quality. In contrast, self-adaptive sensing of the spectrum and changing the communication frequency to a less-interfered channel may greatly improve the communication quality. Another solution is to exploit multiple antennas for beamforming a null point towards the interference sources, which may also greatly improve the communication quality[16]. In this example, the CAMP is inferior to *communication planning* that exploits the frequency and spatial diversity.

B. Evolution to JCMP

Against this background, the evolution from CAMP to JCMP is inevitable, where JCMP aims at *joint exploiting the DoF in mobility, space, time, frequency and energy (MSTFE) dimensions from both the motion and communication components equipped by the robots*. As a result, the wireless-connected robotic networks adopting JCMP will *be capable of covering a wider range of application scenarios* that involves interference and multi-access, etc.

After the differences between the CAMP and JCMP being identified, several research questions are raised in order to be implement CAMP/JCMP in a wireless-connected robotic networks (WCRNs), where the most imperative ones are given as follows:

- How to develop an architecture for WCRN in which the JCMP may be incorporated?
- How to quantify the connectivity quality in WCRNs?
- How to effectively design the JCMP in order to exploit the DoF in MSTFE dimensions?

The rest of the paper would be devoted to the above research questions. Although we try to address the above research questions, it should be noted that it is difficult to address the above questions in a single technical note. Therefore, a trade-off has been made between the proposed architecture design and necessary literature survey due to the space limitations.

In Section II, an OODA-based architecture is proposed in order to address the first question, while in Section III, the second question is approached by a brief overview of the research on connectivity quality assessment in WCRNs. In IV, two categories of JCMP designs are summarized and an illustrative design example is given. Besides, several open problems are put forward along with the conclusions in Section V.

II. OODA-BASED WCRN ARCHITECTURE

In this section, the architecture of the wireless-connected robotic network is proposed, which is motivated by the observe-orient-decide-act (OODA) cognitive-behavioral model[17] and its application in robotic motion control and cognitive radio (CR).

The observe-orient-decide-act (OODA) loop was first proposed by John Boyd in the mid-1950s [17], [18]. Though Boyd initially applied the concept to the military combat operations process, it is now also often applied to a wide variety of areas, such as understanding the commercial operations, the learning processes, etc[19].

A robotic motion control system may be decomposed into a series of functional units, namely, the perception, modeling, planning, task execution and motor control, where the perception is implemented by the sensors for observing the environments, while the task execution and motor control are carried out by the actuators to interact with the environments[20]. Therefore, the robotic motion control system may be modeled as a OODA loop.

The adoption of OODA model in the area of wireless communications may be traced back to 1999, when Mitola. etc propose the concept of CR and explains the cognition cycle[21]. Jayaweera and Christos proposed the concept of *RadioBot* and treated the radio device an equivalence of a robot in mechanical engineering[22]. In the technical note summarizing the developments of CR in 2013[23], Fette explicitly related the CR cognition cycle to the OODA loop model, including *Observe* by measuring the elector-magnetic environment, *Orient* to the mission objective by adapting at different protocol layers, *Decide* by making good performance choices for the mission, and *Act* on the decisions, which is

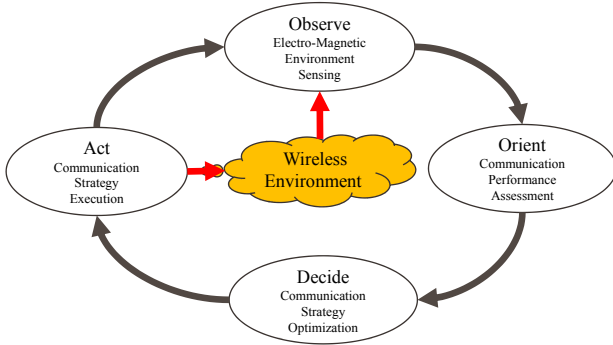


Figure 2. OODA model for a cognitive radio system.

illustrated in Fig. 2. It should also be noted that besides the explicit observe, orient, decide and act procedures, the learning capability is also highlighted in the CR, indicating a CR is capable of continuously self-learning from its past experience in order to improve the performance during the orient and the decide procedures.

Motivated by the OODA loops in the robotic motion control and the cognitive radio, we propose the OODA architecture for WCRNs, which is illustrated in Fig. 3. Traditionally, the two OODA loops are separately designed and implemented, while the WCRN architecture in Fig. 3 fuses both OODA loops in motion control and cognitive radio by incorporating the JCMP, which joint exploits the DoF in MSTFE dimensions.

The information flow in Fig. 3 is as follows. Firstly, the wireless communication devices and the motion sensors implement the communication and motion resource sensing, respectively. Then, the measurements are imported to the respective performance assessment modules and generate a performance quality metric according to the mission objectives, given a communication/motion plan. Afterwards, the JCMP module generates the optimized plan and request the task execution module to take the corresponding actions. As a final remark, the knowledge database supports the performance assessment and the JCMP modules to store and learn from past experiences, as inherited from CR. The information flow in Fig. 3 indicates that the connectivity quality assessment is a requisite for implementing JCMP. Therefore, we provide a overview in the following section.

III. CONNECTIVITY QUALITY METRIC AND ASSESSMENT

Numerous research contributions have been devoted to quantifying the quality of connectivity, which may be divided into two categories. Firstly, the measure of connectivity over a graph is revisited and its disadvantages are discussed in Section III-A, which motivates the research on the second category of realistic channel model based connectivity quality metric (RCM-based CQM). For a more detailed overview of graph-theoretic connectivity quality metric (GT-CQM), please refer to [24].

Compared to the family of graph-theoretic CQM, the family members of RCM-based CQM are much more diverse, e.g. the bit error rate (BER), packet error rate (PER), capacity,

transmission rate, etc. These metrics have been researched in the field of wireless communication for decades[25], and they are task-specific and exhibit a fundamental trade-off, e.g. diversity-multiplexing trade-off, etc [16]. Therefore, it is difficult and unnecessary to include a comprehensive review over this category of connectivity quality metric. Instead, the SoAs of applying RCM-based CQMs in WCRNs will be provided in Section III-B.

A. Graph-theoretic CQM

As a robot may be treated as an intelligent agent, the communication design for a WCRN is reflected in the research on connectivity in multi-agent systems (MAS)[2]. The authors of [26], [27], [28], [24] have considered the scenarios where a group of agents or robots are achieving some mission objective, while addressing the problem of maintaining connectivity during the mission. These contributions mainly adopts graph theory for modeling the network, where the agents or robots are abstracted into nodes in the graph, while the edges represent the communication links between nodes[24]. Within this framework, the most typical metrics for capturing the connectivity in the networks are the algebraic connectivity metric and the number-of-path metric, while both metrics have been widely adopted in a variety of scenarios, e.g. exploration, surveillance, etc. For a comprehensive overview and tutorial of adopting graph-theoretic definition of connectivity, the readers are referred to [2], [24], in which the authors also provided various approaches ranging from convex optimization to potential fields based control methods in order to optimize or maintain communication connectivity in MASs or WCRNs.

Specifically, a network of multiple communication links is modeled by a weighted state-dependent graph, where each link between two nodes i and j at time t is associated with a weight commonly defined as $w_{ij}(t) = f(\|x_{ij}(t)\|)$, and $\|x_{ij}(t)\|$ is the euclidean distance between the pair of nodes and the non-negative weight function $f(\bullet)$ may be of arbitrary shape according to the definition of connectivity. For example, a step-shape weight function

$$w_{ij}(t) = f(\|x_{ij}(t)\|) = \begin{cases} 1 & , x_{ij}(t) < x_{th} \\ 0 & , x_{ij}(t) \geq x_{th} \end{cases} \quad (1)$$

models a connectivity metric, which has perfect connection $w_{ij}(t) = 1$ if the distance between two nodes $x_{ij}(t)$ is smaller than a threshold value x_{th} , and lost connection completely otherwise. The above function is very similar to the outage probability (OP) generally adopted in the analysis and design of wireless networks[25], where an outage or a connection failure occurs when the instantaneous signal-to-noise ratio (SNR) is below a pre-defined value. However, the graph-theoretic definition of connectivity may face the following challenges in robotic networks with realistic wireless channels:

- In general, the QoS over wireless channels cannot be fully captured by a weight function of the distance between two nodes. The distance only determines the path-loss, while the received SNR is also characterized by multi-path fading effects[29].

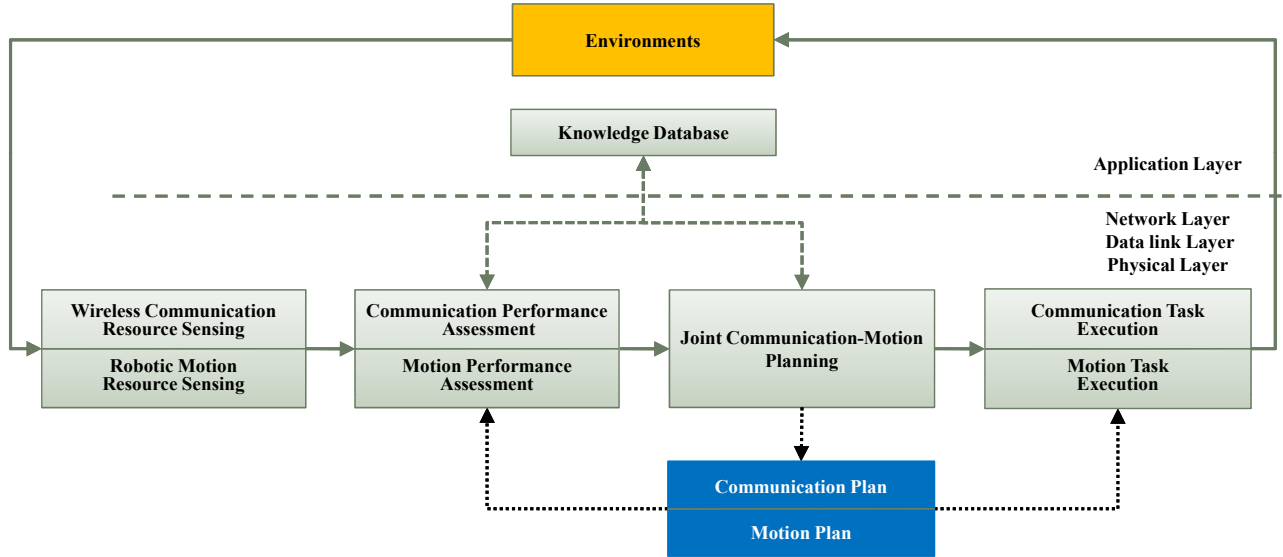


Figure 3. The OODA-based architecture of the wireless-connected robotic networks (WCRNs).

- It is difficult for the algebraic connectivity and number-of-paths metrics to capture the end-to-end communication QoS of links involving multiple hops and diversity in the space, time and frequency domain[9].
- Most current works rely on symmetric weights by assuming a pair of communication links have identical communication quality, which is not practical in asymmetric scenarios. For example, in the unmanned aerial vehicle (UAV) systems, a highly asymmetric data traffic is common, where a high sensing data rate and a low control data rate may co-exist between the UAV and the remote control station[30].

Therefore, although the graph-theoretic CQM has been successfully applied in various applications, a class of CQM metrics which may fully capture the performance over realistic wireless channels was demanded.

B. RCM-based CQM

Against the challenges exhibited in the graph-theoretic connectivity control, the more realistic wireless channel models along with the CQM for quantifying the communication quality-of-service (QoS) have been introduced into the design and control of WCRNs since 2009. Different CQMs may be adopted for physical, data-link and network layers, and the CQMs may be roughly divided into categories that quantify reliability and spectral efficiency, respectively.

In terms of reliability, the BER in uncoded schemes and PER in coded schemes have been widely used CQM metric for quantifying transmission reliability for a variety of physical layer protocols[25]. BER was adopted as the CQM for WCRNs in [15], [31], [13] and PER was adopted in [4], [6]. In terms of spectral efficiency, capacity and transmission rate are widely used CQM and they were introduced to WCRNs in [3], [14]. At higher protocol layers, the end-to-end (e2e) PER and e2e transmission rate may reflect the performance[32],

[33], which were introduced to WCRN applications in [12], [9].

It should be noted that although the definitions and application scenarios of the above mentioned reliability and spectral efficiency CQMs are different, there is a fundamental trade-off so both categories of CQMs may be interchangeable in terms of quantifying the connectivity quality. For example, the diversity-multiplexing trade-off in wireless system design from the information-theoretic perspective [34] and the practical multi-functional multi-input multi-output system design in order to strike the trade-off between spatial diversity, multiplexing and beamforming[35].

IV. JOINT COMMUNICATION-MOTION PLANNING

In this section, we would investigate the third research question proposed in Section I. The JCMP design methods are categorized into single- and multi-stage methods in Section IV-A, followed by an illustrative example in Section IV-B.

A. Single and Multi-Stage Methods

Let us revisit the OODA architecture in Fig. 3. The WCRN implements both the communication and motion resource sensing, where the observations are fed into the performance assessment module. Then, given a specific communication/motion plan, the communication and motion performance are evaluated and fed back to the JCMP module so that an optimized or optimal plan may be found.

From a mathematical perspective, the communication and motion performance are quantified and formulated as *cost functions* (e.g. total energy consumption, etc.) relying on the chosen communication-motion plans. The plans, on the other hand, is modeled as a set of control *variables*. Finally, the availability of communication/motion resources (e.g. transmission power, time, bandwidth, etc.) as well as the mission objectives (e.g. PER, video quality metric, security, etc.) set

several *constraints*. Therefore, for each OODA loop in WCRN, the JCMP module may formulate an optimization problem in order to minimize the cost functions by optimizing the variables, while satisfying certain constraints.

The JCMP methods may be categorized into multi-stage and single-stage methods. In multi-stage methods, the original problem is decomposed into a collection of simpler sub-problems, where the dynamic programming (DP) technique is well-known and widely adopted[36]. In comparison, various tools may be applied to solve the single-stage optimization problem, which may be seen as a special case of the multi-stage counterparts having a single sub-problem. If the problem is convex, the convex optimization tools may be the most efficient choice[37], while a large family of heuristic optimization tools may be selected for solving a non-convex problem[38].

In order to illustrate the differences between the single-stage and multi-stage methods, a multi-robot surveillance example is provided as follows.

B. A Multi-Robot Surveillance Example

We consider a simple WCRN scenario of two robots as illustrated in Fig. 1, where a sensing robot surveys an area and transmits the collected data to a remote base station. However, the distance spanning from the sensing robot to the base station is long, so that the direct transmission cannot support the required communication quality in terms of PER. Therefore, a router robot is deployed for relaying the data transmission from the sensing robot to the base station, where decode-and-forward (DF) is adopted[39]. In order to maintain the required sensing quality received at the base station, the PER should be kept below a pre-defined threshold. The objective is to minimize the total energy consumption of both the sensing and the router robots. Because the sensing robot is assigned to survey the area and track a target, the motion energy of the sensing robot is assumed to be determined by the trajectory of the target and cannot be optimized. Therefore, we focus on optimizing the sum of the router robot's motion and communication energy as well as the sensing robot's communication energy.

The other simulation parameters are set as follows. We adopt the 802.11g protocol as the communication specifications, where the corresponding bandwidth is $B = 20MHz$ and the noise power spectral density is $N_0 = -100dBm/Hz$. The pathloss exponent is $\beta = 3.68$ and Rayleigh quasi-static fading is assumed. Both the router and sensing robots are allowed to adapt transmission power and the per-robot transmit power should be below 4 Watt. The transmission rate is also adaptive by selecting from 6 modes and the PER performance is modeled by the approximate expression proposed by Liu et al[32]. For the PER upper bound, we use an accepted value 0.01. The motion parameters are from the Pioneer 3DX robot and $v_{max} = 1m/s$.

The resulted trajectory of the router robot is given in Fig. 4. Fig. 4(a) is the benchmark called communication-planning, where no JCMP is implemented and the decide module in the OODA loop only considers the minimization of communication energy, and the resulted positions of the

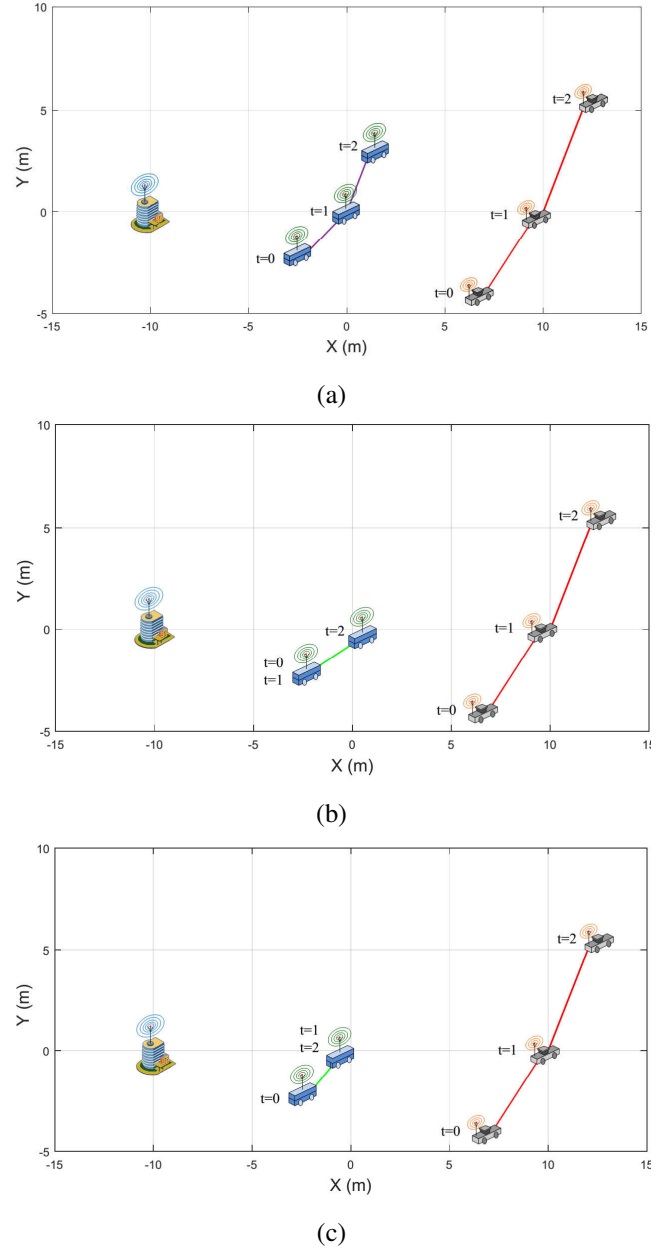


Figure 4. From top to bottom: The comparison of the optimized trajectory of the relay robot based on (b) communication planning (c) single-stage JCMP (d) multi-stage JCMP by value iteration algorithm.

router robot is on the straight line spanning from the sensing robot to the base station for each time step $t = 0, 1, 2$, which was also observed in [39].

Fig. 4(b) shows the optimized trajectory of the router robot with single-stage methods. Specifically, at the beginning of each time step, the sensing robot is only capable of predicting its own position in the current step according to the observations of the unknown target. During each step, the JCMP may optimize the router position in the current step, which is single-stage and the plan consist of 3 control variables, namely, the transmission power of both robots and the position of the router robot. It is observed that the router robot choose not to move in time step $t = 1$. In this way, the motion energy is

conserved and the resulted total energy saving for 2 time steps is 16.9% when compared to the benchmark.

The bottom figure shows the optimized trajectory of the router robot with multi-stage methods. Different from the previous cases, the sensing robot is capable of predicting its own positions for the next two steps. By assuming accurate prediction, the JCMP may optimize the router position for two steps. As seen in Fig. 4(c), the router robots is planned to move in time step $t = 1$ and keep still in time step $t = 2$. The different trajectory of the single- and multi-stage methods is attributed to the availability of knowledge. Compare to the single-stage component, the two-stage method achieves a beneficial energy saving ratio of 17.7% by exploiting the additional knowledge. It should be noted that the energy saving comes at the cost of a significant longer computation time, as in the multi-stage problem, the dimension increases exponentially with the number of stages and the solver are in general less computational-efficient than their single-stage counterparts[40].

V. CONCLUSIONS AND OPEN PROBLEMS

In this technical note, we first reviewed the contributions on WCRNs, with a focus on the CAMP scheme and proposed that JCMP may overcome the disadvantages of CAMP. Then, we proposed the OODA-based WCRN architecture that incorporates JCMP. After reviewing the SoAs in connectivity quality metric for the performance assessment module, the JCMP was discussed in more details and an illustrative example was provided to compare the single- and multi-stage JCMP optimization methods. The final purpose of this technical note is to discuss open problems, which need to be addressed in order to fill the gap between the state-of-the-art and a practical WCRN.

- Firstly, more research efforts need to be devoted to the CQM design and assessment. Although various CQM have been proposed and applied to WCRNs, the robotic applications requires task-oriented mission performance metrics, e.g. sensing video delivery quality[41], [42], detection error probability [6] and networked-control performance metric[43], etc. The other fundamental problem is to provide accurate CQM assessment in practical environments. Most contributions in the literature relies on statistical channel model (including the example provided in Section IV-B), which may over simplify the parameters affecting the CQM in practical system and therefore may incur erroneous assessment that misleads the JCMP design. In order to bridge the gap between theoretical CQM analysis and practical CQM assessment, several contributions have been proposed. For example, Halperin et al. proposed the PER/rate assessment based on practical SNR measurements[44], and Kudelski et al. designed a novel support-vector-machine (SVM) based link quality estimation protocol[10]. However, most CQM methods proposed in the literature considered point-to-point communications, while a WCRN involves multiple inter-connected robots. Therefore, the CQM assessment in multi-access network having a more sophisticated network topology remains an open problem.

- Secondly, more advanced approaches should be applied in JCMP for practical applications. Most publications adopted single-stage optimization tools for solving the CAMP/JCMP problem as in [3], [4], [5], [6], [7], [8], [9], [10], [11]. In order to utilize the past experience and the predicted knowledge, multi-stage JCMP may be adopted and DP is a classic choice. However, the computation complexity induced by the “dimension curses in state space and action space” in DP may prohibit practical applications for WCRNs, which incorporates multiple robots and exploits the DoF from *MSTFE* dimensions[40]. Therefore, the dimension reduction techniques from approximated dynamic programming [40] as well as from machine learning [45] become indispensable. There have been some applications in WCRNs already [46], [47], but the system models and the scenarios considered are quite limited.
- Finally, the WCRN requires motion sensing, motion performance assessment as well as motion execution as illustrated in Fig. 3, hence it demands a platform for implementation, testing and verification in practical scenarios. The WCRN may be treated as one of the enabling technologies in *collective robotics*. The research of collective robotics may involve interdisciplinary efforts in order to deal with the technological, scientific, and social problems in artificial and mixed societies consisting of many interacting entities, which may be *morphable* and *intelligent*[48]. Against this background, we proposed the morphable, intelligent and intelligent robotic operating system (micROS)[49], which is an open-source project and is available at <http://micros.nudt.edu.cn>. The micROS is based on the robot operating system (ROS) project[50], while focuses intensively on morphable resource management, autonomous behavior management in order to support collective intelligence. The micROS is also designed based on the OODA model and JCMP will be released as one of the packages. In order to enable practical CQM assessment, the other package under development supports soft-defined radio (SDR) platform based on GNU-Radio[51].

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